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The Linear Aerospike Engine

In July of 1999 two linear aerospike rocket engines will power the first flight of NASA's X-33 advanced technology demonstrator. A successful X-33 flight test program will validate the aerospike nozzle concept, a key technical feature of Lockheed Martin's VentureStar™ reusable launch vehicle. The aerospike received serious consideration for NASA's current space shuttle, but was eventually rejected in 1969 in favor of high chamber pressure bell engines, in part because of perceived technical risk. The aerospike engine (discussed below) has several performance advantages over conventional bell engines. However, these performance advantages are difficult to validate by ground test. The space shuttle, a multibillion dollar program intended to provide all of NASA's future space lift could not afford the gamble of choosing a potentially superior though unproven aerospike engine over a conventional bell engine. The X-33 demonstrator provides an opportunity to prove the aerospike's performance advantage in flight before committing to an operational vehicle. What is this radical looking new rocket engine, how does it differ from other rocket engines, and why was it selected for VentureStar™?

The linear aerospike engine is one of a family of potential engine concepts using an external expansion or "plug" nozzle. In some ways it resembles an inside out engine. In a conventional rocket engine the hot propellant gases expand through an axisymmetric converging diverging bell nozzle. In the aerospike engine one side of the supersonic expansion is a centerbody or "plug." The other side is a free streamline. The free streamline produces a performance advantage for rocket engines designed to operate both deep in the atmosphere and at vacuum as in a single stage launch vehicle. The surrounding ambient pressure at low altitude restricts the expansion of the exhaust gas. A shock wave forms on the plug, raising the engine exhaust pressure to match the surrounding ambient pressure. As altitude increases the ambient air pressure is reduced, the exhaust expands farther and the shock wave moves down the plug. Eventually, at high altitude it moves off the plug all together. In a conventional rocket engine, a high area ratio bell nozzle can expand the exhaust to pressures lower than the surrounding atmosphere. The suction from this low pressure region can actually reduce the engines net thrust, and produce damaging side loads on the nozzle. For a given chamber pressure and fixed engine geometry the maximum allowable overexpansion at low altitude limits the maximum feasible nozzle area ratio. Since vacuum performance is a function of area ratio maximum allowable overexpansion at sea level limits the maximum vacuum performance of a bell engine. The altitude compensating feature of the plug nozzle allows higher nozzle area ratios in earth-to-orbit applications, resulting in higher performance.

While the aerospike's response to the surrounding ambient pressure is the basis for its altitude compensating capability, it also introduces an element of uncertainty. Airflow over the base of the vehicle can result in pressure below ambient at the nozzle exit causing the nozzle to overexpand with a resultant

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performance loss. This loss is most pronounced when operating near transonic Mach numbers low in the atmosphere. Although transonic windtunnel testing with powered models can be used to predict the installed performance of vehicles with aerospike engines, the ability to simulate a hot rocket engine exhaust at full nozzle pressure ratio is very limited. For X-33, initial aerospike performance predictions will be derived from the transonic windtunnel results supported by computational fluid dynamic modeling. The final validation of the aerospike performance and prediction models will be the actual flight of the X-33.

The name aerospike originated in 1959. Rocketdyne's Advanced Studies Group was attempting to reduce the cost of nozzles for small tactical rocket engines. Rocketdyne tested a concept in which two coaxial jets were allowed to expand in a tube. One jet was at higher pressure than the other. In theory the high pressure jet would expand into the low pressure jet, causing it to "choke," producing a sonic nozzle. An aft facing cone was added to the inner lower pressure annulus which increased the thrust coefficient above that of the simple sonic nozzle. The term aerospike refers to the spike shape of the free streamline separating the outer annulus flow from inner annulus flow. In order to generate thrust the pressure of the expanding gas must push against a surface, in this case the aft facing cone or "plug." The aerospike nozzle differs from a conventional plug nozzle in that the gas in the inner annulus pressurizes the base of the plug producing more thrust than a conventional plug. The aerospike nozzle is particularly well suited for rocket engines utilizing a gas generator power cycle. In the gas generator cycle propellant is combusted and expanded through turbines to drive the engine's propellant pumps and then dumped overboard without passing through the main combustion chamber of the engine. The turbine drive gas which normally produces little or no thrust may be used to provide the base pressurization gas for the aerospike nozzle. The additional thrust resulting from the base pressurization allows a gas generator cycle engine to approach that of a conventional bell nozzle engine using the higher performing but more complex and difficult to develop staged combustion cycle.

The length of a supersonic nozzle may be shortened with no loss in thrust coefficient by turning the flow more rapidly at low Mach number and reducing the turning at high Mach number. This is the basis for the evolution from simple conical nozzles to the high performance bell nozzle designs common in today's engines. In the plug nozzle the low supersonic Mach number turning occurs on the outer radius resulting in more area change for the same angle change. When designed for equivalent levels of performance, plug nozzles are physically shorter than conventional nozzles making them attractive whenever volume is constrained. The short length of the aerospike concept made it attractive for upper stage engines where the length of the interstage structure adds structural weight to the vehicle. Rocketdyne studied derivatives of the J-2 engine for the upper stages of advanced versions of the Saturn V vehicle. The proposed J-2 aerospike engines for Saturn V were axisymmetric and substituted directly for the J-2 bell engines. Thrust vector control was provided by gimbaling the engine just as in a conventional bell.

However, a fully integrated aerospike design can reap considerable weight savings by using a common load path for the engine and vehicle. The heavy thrust structure required to carry the load from the gimbal bearing to the shell of the propellant tank is avoided. In order to take advantage of this potential weight saving, an alternative approach to thrust vector control is required. By differentially throttling each side of a linear aerospike engine it is possible to shift the thrust vector without gimbaling the thrust chamber. To understand how this is possible consider one side of a linear aerospike thrust chamber. The thrust may be divided into components generated by the internal surfaces of the modular thruster and the external surface of the ramp. The sum of these forces produces both an axial force and a side force. The side force is canceled by the equal and opposite force generated on the opposing thrusters and ramp on the other side of the engine. If one side of the engine is throttled down and the opposite side is throttled up then a net side force is generated while the sum of the axial forces is constant. The differential throttling of the two sides of the engine is provided with valves in the propellant feed lines between the turbopumps and the thrust chamber. The power required to actuate the differential throttling valves is considerably less than that required to gimbal a large rocket engine and is easily satisfied with electromechanical actuators. The linear aerospike is particularly amenable to this design because it can provide thrust vector control in all three axis. For pitch, thrust chambers above and below the vehicle center line are differentially throttled in the same direction. To provide roll, opposing outboard engine are differentially throttled in opposite directions. Finally yaw is provided by throttling the whole engine assembly up or down in thrust on opposite sides of the vehicle.

When work began on the Space Shuttle in the late 1960s, the aerospike became the basis of Rocketdyne's initial engine approach, and Lockheed's StarClipper shuttle concept used a fully integrated linear aerospike engine, a preview of things to come. Other contractors proposed clusters of axisymmetric aerospikes. Late in the concept phase, however, the vehicle designs were revised to accept only bell nozzles. While most of Rocketdyne turned to develop the Space Shuttle Main Engine, a small group continued with the development of two Linear System Test Bed demonstrator engines using a gas generator cycle to power turbomachinery originally developed for Rocketdyne's J-2S engine. These successful test bed engines at 250,000 and 125,000 lbs of thrust (at vacuum) were the first full engine tests of the aerospike engine concept. As defined by Rocketdyne in the 1960's the aerospike thrust chamber consisted of a continuous annular throat around a central plug. Test thrust chambers of this design experienced serious throat cooling and acoustic combustion instability problems. The acoustic instability was solved by dividing the thrust chamber into independent modules of rectangular cross sections. These modules could be arranged around a central plug of axisymmetric, linear or oval cross section. The linear system test bed engines used modular rectangular thrusters on two opposing sides of a rectangular plug.

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The X-33's linear aerospike engines are derived from the linear test bed engines. They will use the same J-2S turbomachinery as the test bed and mount 20 modular thrusters 10 each on opposing sides of a rectangular plug. The gas generator that powers the turbomachinery is a modification of the J-2 engine gas generator. However, the original rectangular modular thrusters will be replaced with more robust round thrusters that transition to a rectangular exit. The round throat thruster has significantly lower cooling requirements (less wetted area) and is more efficient structurally than a rectangular throat thruster. As the engine does not utilize a continuous annular throat it would be more technically accurate to describe it as a modular linear plug nozzle with base pressurization. The thrusters will be fabricated using a pressure brazing technique developed for the space shuttle main engine "large throat" combustion chamber program. The linear system test beds used an actively cooled plug made by brazing tubes together and supported with stringers and hat bands. In the X-33 engine, the brazed tube assembly is replaced by a copper panel with machined cooling channels. The cooling channels are closed out with a brazed face sheet and supported by a honeycomb structure. For X-33 the pitch and roll thrust vector control will be provided by differentially directing fuel from one side of the engine to the other using electromechanically actuated valves in the propellant lines. In order to accommodate the pressure drop of the differential throttling valves, the X-33 chamber pressure was reduced relative to the linear test beds. The area ratio of the engine was reduced as well. Yaw control will be provided by throttling the whole engine assembly up and down in thrust. As originally proposed, the X-33 engine would have incorporated propellant manifolding to split the propellant flow from two turbopump sets (one set of oxygen and hydrogen turbopumps for each engine) between an inner bank of thrusters and two outer banks of thrusters to maintain symmetric thrust in an engine out situation. This scheme was later replaced by propellant manifolding which would feed all thruster banks simultaneously from one set of pumps in the event the other pump set fails in flight.

The engine for the VentureStar™ Reusable Launch Vehicle is expected to incorporate a significantly more advanced set of component technologies. Fiber reinforced ceramic matrix composites in the fuel pump turbine will permit higher turbine inlet temperatures for higher specific impulse. The copper external expansion plug will be replaced with an actively cooled ceramic matrix composite nozzle and the thrust structure will be composite as well. Each individual engine will be approximately twice the thrust of the X-33 engine and the VentureStar™ vehicle will have 7 engines as compared to 2 in the X-33. With more engines, the VentureStar™ will have a genuine engine out capability without resorting to the propellant manifolding schemes used on X-33. The thrust chamber and nozzle concept will be similar to the X-33 from a fluid dynamic standpoint. However, the VentureStar™ engine will operate at more than twice the X-33 engine chamber pressure with a correspondingly higher area ratio. Other advanced technologies proposed for the VentureStar™ engine include health monitoring and LASER ignition.

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The single stage earth to orbit reusable launch vehicle is arguably the most demanding rocket propulsion application ever attempted, but the potential payoff in lower launch cost and operability is dramatic. An engine with high thrust to weight and high specific impulse is a necessary requirement to achieve this goal. However, a commercially viable reusable launch vehicle cannot sacrifice life and operability to achieve high performance. Nor can it afford the development budgets typical of government space and defense programs at the height of the cold war. The altitude compensating linear aerospike engine operating on oxygen and hydrogen propellants produces high performance with a simple gas generator power cycle. Both altitude compensation and thrust vector control are provided without variable geometry or gimbaling, and the vehicle and engine load paths can be integrated for significant weight savings. When coupled with an innovative lifting body vehicle, the road not taken after 1973 now promises a revolution in space transportation.